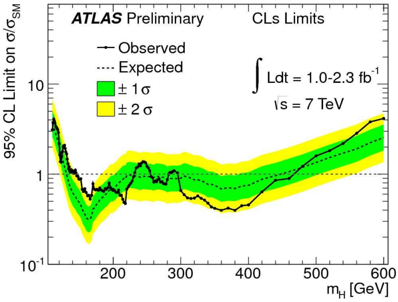
# Automated one-loop calculations with Golem/Samurai

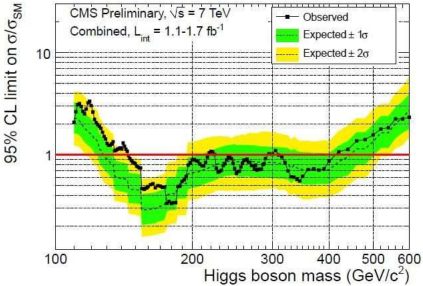
Gudrun Heinrich

Max-Planck Institute for Physics, Munich

ACAT conference
Brunel University, London, 08.09.2011

# Motivation


ATLAS Preliminary
CLs Limits
Observed
Expected
± 1σ
± 2σ
∫ Ldt = 1.0-2.3 fb⁻¹
√s = 7 TeV
95% CL Limit on σ/σSM
m_H [GeV]


CMS Preliminary, √s = 7 TeV
Combined, L_int = 1.1-1.7 fb⁻¹
Observed
Expected ± 1σ
Expected ± 2σ
95% CL limit on σ/σSM
Higgs boson mass (GeV/c²)

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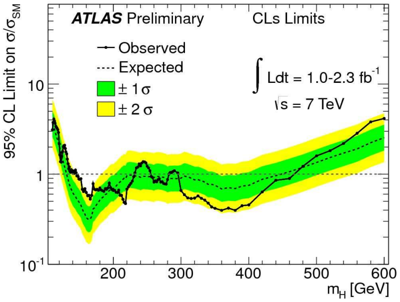
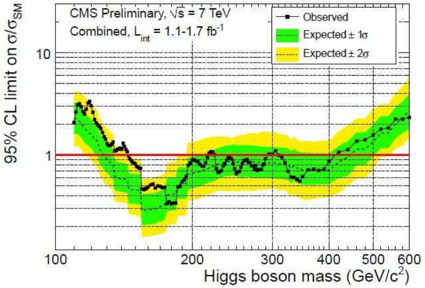


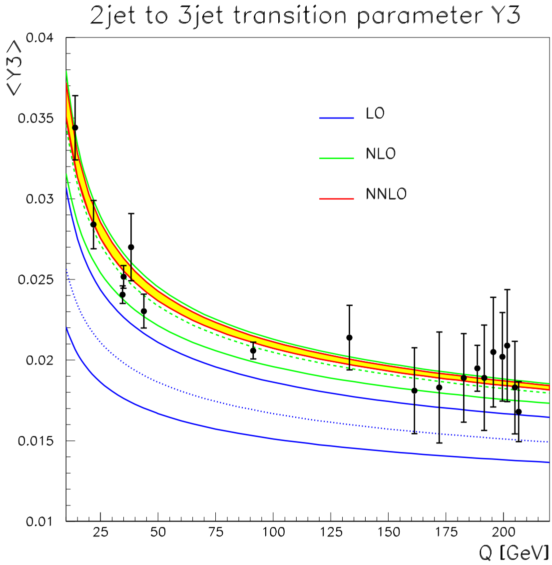

we need precise theory predictions for "Expected" !

# N(N)LO

predictions beyond leading order:

- reduction of scale dependence
- reliable estimate of absolute rates
- better description of jets
- better PDF fits
- ...

# N(N)LO




example:

3-jet observable

in $e^+e^-$ annihilation

[A. Gehrmann-De Ridder, T. Gehrmann, N. Glover, GH '09]

uncertainty bands:

$M_Z/2 < \mu < 2\,M_Z$

# some NLO multi-leg highlights

- $pp \to W^+W^-b\bar{b}$ Denner,Dittmaier,Kallweit,Pozzorini '10, Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek '11
- $pp \to W/Z + 4$ jets BlackHat collaboration '10/'11
- $pp \to Z/\gamma + 3$ jets BlackHat collaboration '11
- $pp \to t\bar{t} + 2$ jets Bevilacqua, Czakon, Papadopoulos, Worek '10
- $pp \to W^+W^+jj$ Melia, Melnikov, Rontsch, Zanderighi '10
- $pp \to W^+W^-jj$ Melia, Melnikov, Rontsch, Zanderighi '11
- $gg \to b\bar{b}b\bar{b}$ Greiner, Guffanti, Reiter, Reuter '11
- EW corrections to dilepton+jet production Denner,Dittmaier, Kasprzik, Mück '11
- $e^+e^- \to 5$ jets Frederix, Frixione, Melnikov, Zanderighi '10

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- also: BIG advances in automation

# Automated NLO Tools

## One-loop

- FeynArts/FormCalc/LoopTools (public) Thomas Hahn et al
- Helac-NLO Bevilacqua, Czakon, van Hameren, Papadopoulos, Pittau, Worek
- MadLoop Hirschi,Frederix,Frixione,Garzelli,Maltoni,Pittau

  uses CutTools (public [Ossola, Papadopoulos, Pittau]) and MadFKS
- Golem-Samurai (Samurai public [Mastrolia, Ossola, Reiter, Tramontano])

  Cullen, Greiner, GH, Luisoni, Mastrolia, Ossola, Reiter, Tramontano
- NGluon (public) [Badger, Biedermann, Uwer]
- dedicated programs also involve high level of automation

  Denner, Dittmaier, Pozzorini et al, VBFNLO coll., MCFM, Blackhat, Rocket, ...

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automation of subtraction for IR divergent real radiation

- MadDipole Frederix, Greiner, Gehrmann 08
- Dipole subtraction in Sherpa Gleisberg, Krauss 08
- TevJet Seymour Tevlin 08
- AutoDipole Hasegawa, Moch, Uwer 08,09
- Helac-Phegas Czakon, Papadopoulos, Worek 09; polarized
- MadFKS Frederix, Frixione, Maltoni, Stelzer 09

# Golem-Samurai (GoSam)

General One-Loop Evaluator of Matrix elements &
Scattering Amplitudes from Unitarity based Reduction At Integrand level
[ Cullen, Greiner, GH, Luisoni, Mastrolia, Ossola, Reiter, Tramontano ]

- algebraic generation of D-dimensional integrands based on Feynman diagrams
  - QCD, EW, BSM
  - uses QGraf [Nogueira], FeynRules [Duhr et al], Form/Spinney [Vermaseren/Cullen et al], Haggies [Reiter] to generate integrands

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- reduction by D-dimensional extension of cut-based method
  options:
  - OPP-type reduction
    [Ossola, Papadopoulos, Pittau; Ellis, Giele, Kunszt, Melnikov]
  - traditional tensor reduction (using golem95 library)
  - tensorial reduction at integrand level GH, Ossola, Reiter, Tramontano '10

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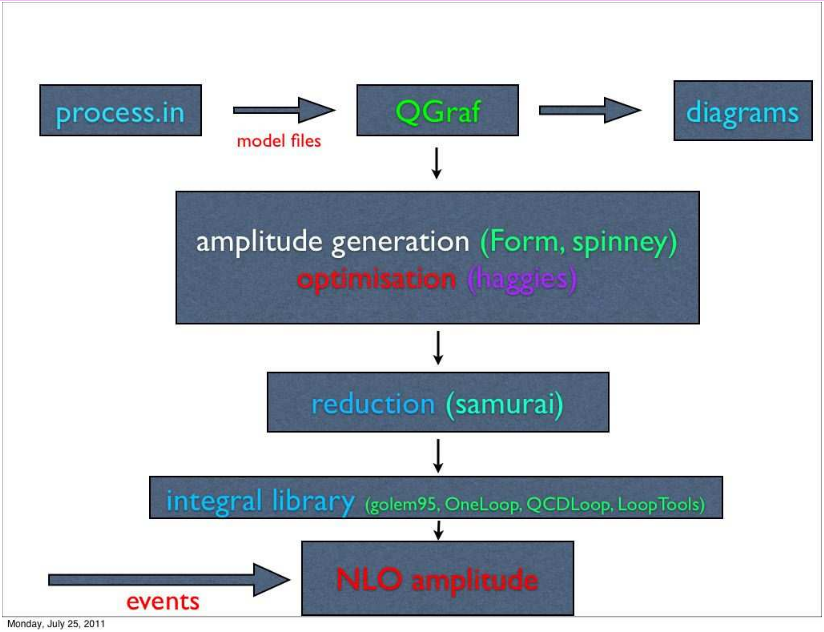
- interface with existing tools for real radiation
  (MadGraph/MadEvent, Sherpa, PowHeg, . . . )

# Golem-Samurai structure



# Golem-Samurai

public release this autumn

usage:

- edit "input card"

```
in= u,d~
out= nmu, mu+, e-, ne~, s~, c
model=smdiag
    models can be added via FeynRules (Duhr) or LanHEP (Semenov)
order=gw,4,4; order=gs,2,4
zero=mB,mC,mS,mU,mD,me,mmu
one=gs,e
helicities=-+-+-++-
extensions=samurai, dred
```

- golem-main.py process.in

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- golem-main.py process.in
- make doc ⇒ documentation and diagram pictures
- make source ⇒ source files
- make compile ⇒ fully compiled code

# Example $u\,\bar{d} \to W^- W^+\,\bar{s}c \to e^-\bar{\nu}_e\mu^+\nu_\mu\,\bar{s}c$

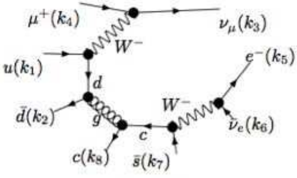



Diagram 1

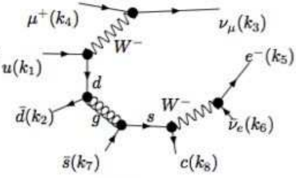



Diagram 2

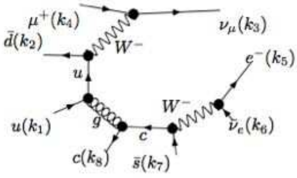



Diagram 3

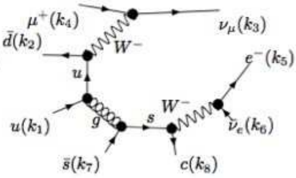



Diagram 4

## 5 One-Loop Diagrams

**General Information**

QGraf Setup

# Example $u\,\bar{d} \to W^- W^+ \,\bar{s} c \to e^- \bar{\nu}_e \mu^+ \nu_\mu \,\bar{s} c$

## NLO sample diagrams

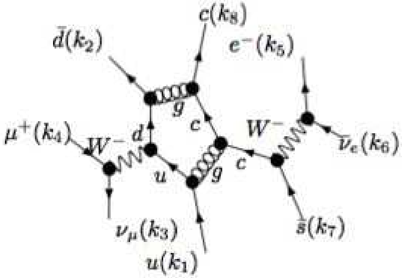



Diagram 8

$S' = S^{\{4\}}_{Q \to -q-(k3-k2+k4)}$, rk = 3

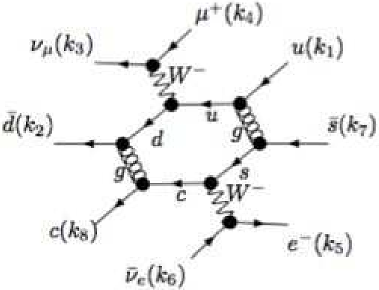
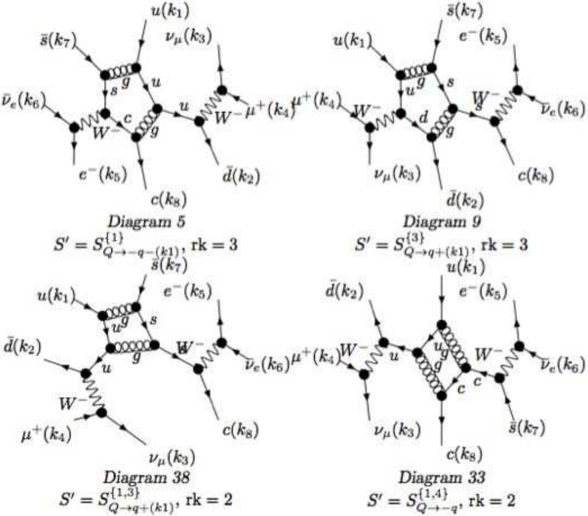



Diagram 1

$S' = S_{Q \to q+(k1)}$, rk = 4

# Example $u\,\bar{d} \to W^- W^+ \,\bar{s}c \to e^- \bar{\nu}_e \mu^+ \nu_\mu \,\bar{s}c$



# Example $u\,\bar{d} \to W^- W^+ \,\bar{s}c \to e^- \bar{\nu}_e \mu^+ \nu_\mu \,\bar{s}c$

code generation:

```
Form is processing loop diagram 80 @ Helicity 0
  2.72 sec out of 2.74 sec
Haggies is processing abbreviations for loop diagram 80 @ Helicity 0
Form is processing loop diagram 81 @ Helicity 0
  0.71 sec out of 0.73 sec
Haggies is processing abbreviations for loop diagram 81 @ Helicity 0
Form is processing loop diagram 82 @ Helicity 0
  0.73 sec out of 0.75 sec
Haggies is processing abbreviations for loop diagram 82 @ Helicity 0
Form is processing loop diagram 83 @ Helicity 0
  0.70 sec out of 0.71 sec
Haggies is processing abbreviations for loop diagram 83 @ Helicity 0
Form is processing loop diagram 84 @ Helicity 0
  0.73 sec out of 0.73 sec
Haggies is processing abbreviations for loop diagram 84 @ Helicity 0
Form is processing loop diagram 85 @ Helicity 0
```

# Example $u\,\bar{d} \to W^- W^+\,\bar{s}c \to e^-\bar{\nu}_e\mu^+\nu_\mu\,\bar{s}c$

```
==========================================================
                   GoSam-1.0
==========================================================

#    NLO/LO, finite part:  -15.91575118714612
#    NLO/LO, single pole:    7.587050495888512
#    NLO/LO, double pole:  -5.333333333333234

 CPU time (secs):    1.2997999999999991E-002
```

result compared with

Melia, Melnikov, Rontsch, Zanderighi (MMRZ) 1104.2327 [hep-ph]

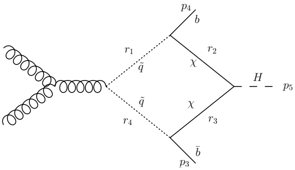
| NLO/LO | GoSam | MMRZ |
|---|---|---|
| $1/\epsilon^2$ | -5.333333333 | -5.333333 |
| $1/\epsilon$ | 7.5870504959 | 7.587051 |
| finite | -15.915751119 | -15.91575 |

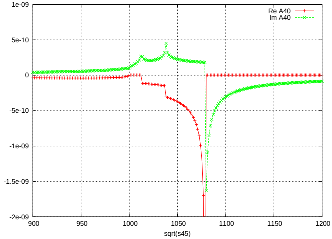
# Tested 5- or 6-point processes

- $u\,\bar{d} \to W^+\,s\bar{s} \to e^+\nu_e\,s\bar{s}$
- $u\,\bar{d} \to W^+\,gg \to e^+\nu_e gg$
- $d\,\bar{d} \to Z\,gg \to e^+e^-\,gg$
- $u\,\bar{d} \to W^+\,b\bar{b} \to e^+\nu_e\,b\bar{b}$ also with massive b's
- $u\,\bar{d} \to W^+\,g \to e^+\nu_e\,g$ EW corrections
- $e^+e^- \to Z \to d\,\bar{d}\,g$
- $\gamma\gamma \to \gamma\gamma\gamma\gamma$
- $q\,\bar{q} \to b\bar{b}b\bar{b}$
- $gg \to b\bar{b}b\bar{b}$
- $u\,\bar{d} \to W^+W^+\,s\bar{c} \to e^+\nu_e\mu^+\nu_\mu\,s\bar{c}$
- $u\,\bar{u} \to W^+W^-\,\bar{c}c \to e^-\bar{\nu}_e\mu^+\nu_\mu\,\bar{c}c$
- $u\,\bar{d} \to W^+W^-\,s\bar{c} \to e^-\bar{\nu}_e\mu^+\nu_\mu\,\bar{s}c$
- plus a large number of $2 \to 2$ processes

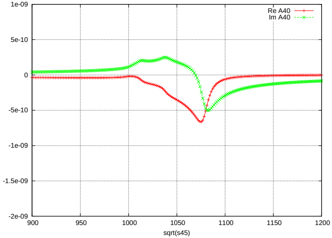
# golem95 integral library

Example: production of a heavy neutral MSSM Higgs and a $b\bar{b}$ pair with unstable particles (squarks, neutralinos) in the loop




real masses




complex masses

contained in golem95C library: 1101.5595 [hep-ph]

http://projects.hepforge.org/∼golem/95/

# Numerical stability

several detection and rescue systems

- local/global $N = N$ test: use decomposition of numerator function after coefficients have been determined:

$$
\begin{aligned}
N(\bar{q}) = & \sum_{i<<m}^{n-1} \Delta_{ijk\ell m}(\bar{q}) \prod_{h\neq i,j,k,\ell,m}^{n-1} D_h + \\
+ & \sum_{i<<\ell}^{n-1} \Delta_{ijk\ell}(\bar{q}) \prod_{h\neq i,j,k,\ell}^{n-1} D_h + \sum_{i<<k}^{n-1} \Delta_{ijk}(\bar{q}) \prod_{h\neq i,j,k}^{n-1} D_h + \\
+ & \sum_{i<j}^{n-1} \Delta_{ij}(\bar{q}) \prod_{h\neq i,j}^{n-1} D_h + \sum_{i}^{n-1} \Delta_{i}(\bar{q}) \prod_{h\neq i}^{n-1} D_h
\end{aligned}
$$

  and compare with original numerator for

  - local: comparison only for specific cuts
  - global: compare full numerator function at arbitrary $q$ values

# Numerical stability

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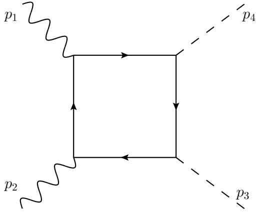
- pole test
- power test: check certain combinations of coefficients which should sum to zero if reconstruction was successful
  (e.g. if power of integration momentum is higher than in original function)
- tensorial reconstruction

# Numerical stability

Example: massless fermion loop with two light-like and two massive legs

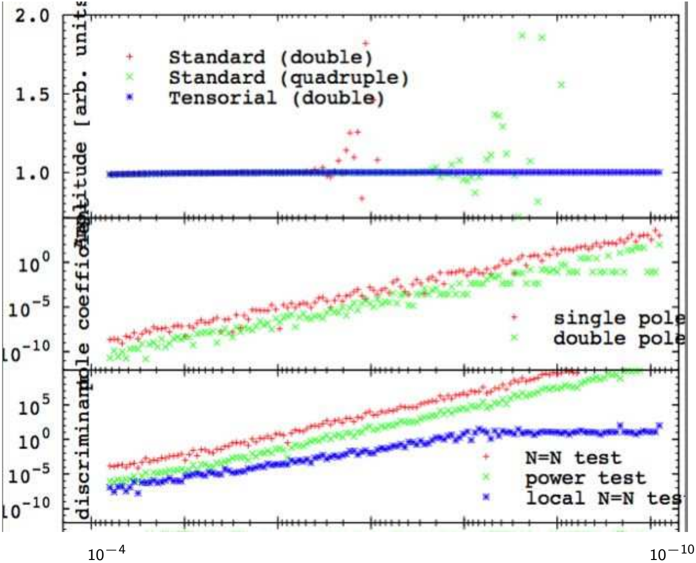
$$
\begin{aligned}
p_{1,2} &= (E, 0, 0, \pm E) \\
p_{3,4} &= (E, 0, \pm Q \sin\theta, \pm Q \cos\theta) \\
E &= \sqrt{M^2 + Q^2}\ ,\ p_{3,4}^2 = M^2
\end{aligned}
$$




$\det G = 32 E^4\, Q^2 \sin^2\theta$

investigate limit $Q^2 \to 0$

# Numerical stability




$m^2 \det G / \det S$

# Tensorial reconstruction

rewrite numerator function as a linear combination of tensors

$$\mathcal{N}(q) = \sum_{r=0}^{R} C_{\mu_1\ldots\mu_r} q_{\mu_1} \ldots q_{\mu_r}$$

$$C_{\mu_1\ldots\mu_r} q_{\mu_1} \cdots q_{\mu_r} = \sum_{(i_1,i_2,i_3,i_4)\vdash r} \hat{C}^{(r)}_{i_1\, i_2\, i_3\, i_4} \cdot (q_1)^{i_1} (q_2)^{i_2} (q_3)^{i_3} (q_4)^{i_4}$$

determine the coefficients by sampling $q$ in a bottom-up approach

Level 0:

$$q = (0,0,0,0)\ ,\ \mathcal{N}(0,0,0,0) \equiv \mathcal{N}^{(0)} = C_0$$

Level 1: 4 systems, each sampling a monomial depending on one component of $q$ only

$\mathcal{N}^{(1)}(q) \equiv \mathcal{N}(q) - \mathcal{N}^{(0)}$

$$q = (x,0,0,0) \quad \Rightarrow \quad \mathcal{N}^{(1)}(q) \equiv x\, C_1 + x^2\, C_{11} + \ldots + x^R\, C_{\underbrace{11\ldots1}_{R\ \text{times}}}$$

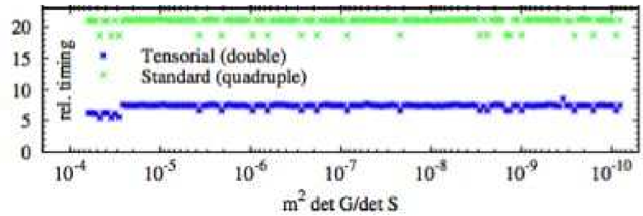
$$q = (0,y,0,0) \quad \Rightarrow \quad \mathcal{N}^{(1)}(q) \equiv y\, C_2 + y^2\, C_{22} + \ldots + y^R\, C_{\underbrace{22\ldots2}_{R\ \text{times}}}$$

$$\ldots$$

# Tensorial reconstruction

advantages:

- tensor basis avoids numerical instabilities due to vanishing Gram determinants (as the latter occur in the reduction to a scalar basis)
- "rescue-system": unstable points will be reprocessed automatically using tensorial decomposition + tensor integrals from golem95



# Tensorial reconstruction

further advantage:

- reconstructed tensor integrand can be used as input for the "standard" reduction (more efficient, as kinematic information is already stored in the tensorial coefficients, disentangles part of integrand depending on the loop momenta from dependence on kinematic invariants)
- $\Rightarrow$ "hybrid method": even for stable phase space points, feeding the reconstructed tensor integrand to the reduction can improve the timings:

| # Lines | Time ratio "hybrid"/standard | |
|---|---|---|
| N | Rank = 4 | Rank = 6 |
| 1 | 1.3 | 1.6 |
| 10 | 1.1 | 1.4 |
| 100 | 0.51 | 0.85 |
| 1000 | 0.30 | 0.59 |
| 10000 | 0.27 | 0.55 |

# Options

reduction:

- samurai, sampling of groups of diagrams
- samurai, sampling of individual diagrams
- tensorial reconstruction + samurai
- tensor reduction with golem95
- samurai + tensor reduction with golem95 if reconstruction fails
- tensorial reconstruction with PJFry [V.Yundin]

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scalar integral libraries: optionally

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- QCDLoop Ellis, Zanderighi
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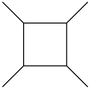
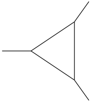
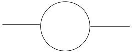
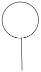
renormalisation/regularisation schemes:

- 't Hooft/Veltman
- DRED (dimensional reduction)
- CDR (conventional dimensional regularisation)
- on-shell (mass counter terms for massive quarks)

# Rational Parts

$\mathcal{A} = C_4$  $+ C_3$  $+ C_2$  $+ C_1$  $+ \mathcal{R}$

two categories: $\mathcal{R} = R_1 + R_2$ [Ossola, Papadopoulos, Pittau]

$$N(q) = \hat{N}(\hat{q}) + \tilde{N}(q, \mu^2, \epsilon)\ ,\ q^2 = \left(\hat{q}^{(4)}\right)^2 - \tilde{q}^2 = \hat{q}^2 - \mu^2$$

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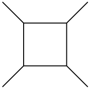
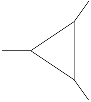
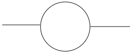
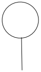
$\mathcal{A} = C_4$  $+ C_3$  $+ C_2$  $+ C_1$  $+ \mathcal{R}$

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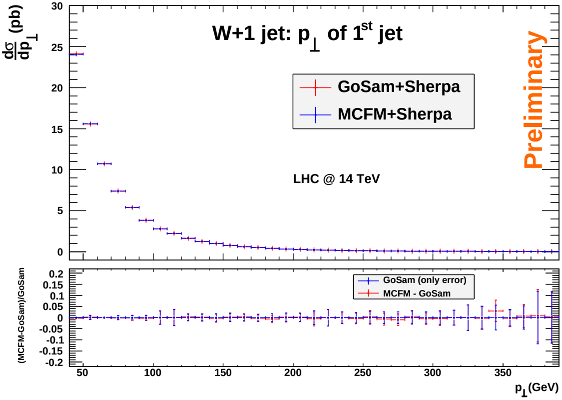
Golem-Samurai offers different options for calculation of $R_2$

- implicit: $\mu^2$ terms are kept in the numerator and reduced at runtime
- explicit: $\mu^2$ terms are reduced analytically
- only: only the $R_2$ term is kept in the final result

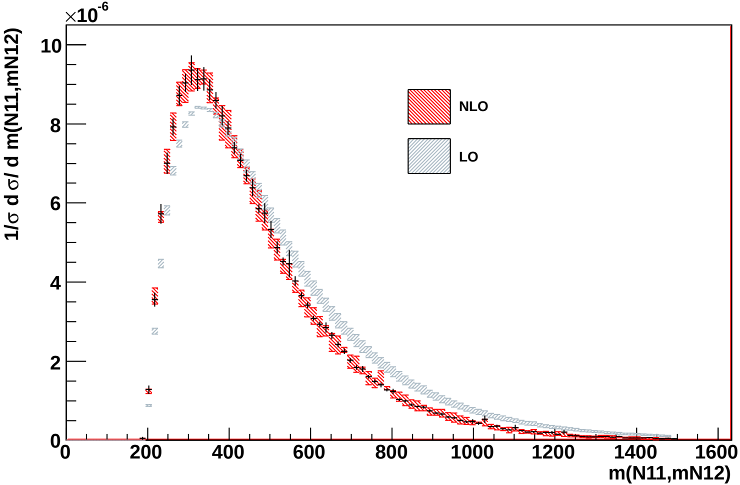
  (does not require any additional libraries)
- off: all $\mu^2$ terms are set to zero

# Interface

- standard interface to real radiation programs (Binoth Les Houches Accord) implemented
- tested with Sherpa and Powheg
- example $pp \to W+$jet [figure by G. Luisoni, J. Archibald]



# Example MSSM: $pp \rightarrow \chi_1^0 \chi_1^0$




[figure by G. Cullen, N. Greiner]

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- public release of full package planned for this autumn !